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Analysis of Current Technology on Electrical Connections in Residential Branch Circuit Wiring

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Analysis of Current Technology on Electrical Connections in Residential Branch Circuit Wiring

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Contents

ADDENDUM TO NATIONAL BUREAU OF STANDARDS BSS 63 (MAR. 75) by Meese and Cilimberg

In late 1973, the Consumer Product Safety Commission requested the National Bureau of Standards to investigate the safety of aluminum branch circuit wiring in homes. This work included the evaluation of reports on the hazards, study of technical work of other organizations, and a technical study of the problem. The work at the National Bureau of Standards continued actively through 1974.

The NBS Programmatic Center for Consumer Product Safety issued a special report to the Commission on this subject, NBSIR 75-723 -- Aluminum Branch Circuit Wiring in Residences; Summary Report for the Consumer Product Safety Commission, January-September, 1974. This report is available for purchase from the National Technical Information Service, Springfield, Va., 22151, as is another NBS report, NBSIR 75-677 -- Hazard Assessment of Aluminum Electrical Wiring in Residential Use, published under date of March 27, 1975.

The Consumer Product Safety Commission held Public Hearings on the Safety of Aluminum Wire in Washington, D.C. in March 1974, and in Los Angeles in April 1974. An abstract of these hearings is included in NBSIR 75-723.

ERRATA TO BSS 63

Replace Figure 6 (p.9) with the following:

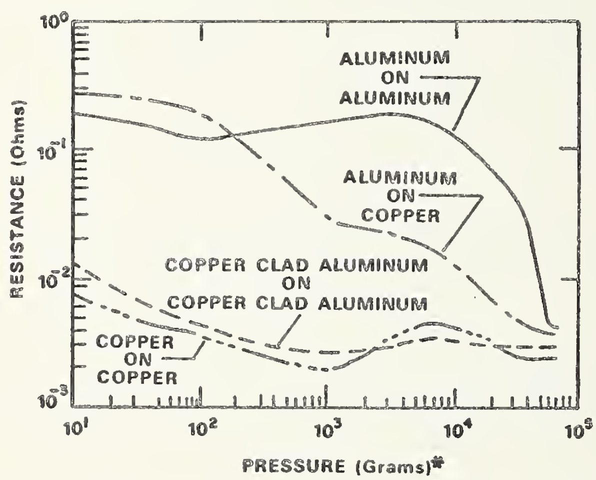

Figure 6. Contact Resistance versus Pressure (Two Conductors Crossed Under Load).

*Force (grams) — one gram-force = .009806650 newton

An Analysis of Current Technology on Electrical Connections in Residential Branch Circuit Wiring

William J. Meese and Ramon L. Cilimberg

In the Operation BREAKTHROUGH research and demonstration program the U.S. Department of Housing and Urban Development became concerned with the inability to properly evaluate innovative eletcrical connections. Long life requirements, fire safety considerations, the lack of adequate technical information, and long established conventional practices and evaluation procedures have led to slow-changing regulations concerning electrical connections used in branch circuit wiring in housing. This report discusses the present methods of evaluating electrical connections, the technical parameters involved, and innovative electrical connection developments. Innovations involving electrical connections may lead to significant advancements in housing construction if it can be demonstrated that functional and safety requirements over the expected life of the electrical connections are adequately satisfied. Research is needed to enable prediction of long-term performance of electrical connections based on the results of accelerated performance tests.

Key words: Contact resistance; electrical codes; electrical connections; fire safety; house wiring; materials properties; performance testing.

1. Introduction

In 1969 the U.S. Department of Housing and Urban Development initiated the Operation BREAKTHROUGH program; one of its purposes was to encourage and demonstrate innovations in housing [1, 2, 3, 4].[1] In the Operation BREAKTHROUGH program several innovations involving electrical connections were proposed, including connections which would be inaccessible after completion of building construction. Conservative reviews were required due to the fire hazard potential and the lack of durability and other technical information available. Approvals for innovations involving electrical systems were sparingly given. However, the possibilities of almost immediate significant breakthroughs were recognized.

The U.S. Department of Housing and Urban Development agreed to sponsor at the National Bureau of Standards a long-range research project on electrical connections in residential branch circuit wiring. The long-range goal of this project is to develop criteria and test methods for evaluating innovative electrical connections. This report is the first publication for this project.

1.1. Scope

This report covers the state of the art of electrical connections used in branch circuit wiring in housing. "Branch circuit" is defined by the National Electrical Code [5] as:

> A branch circuit is that portion of the wiring system between the final overcurrent device protecting the circuit and the outlet(s). A device not approved for branch circuit protection such as thermal cutout or motor overload protective device is not considered as the overcurrent device protecting the circuit.

Branch circuits in housing are generally limited to nominal 115 or 230 volts with rated ampacity (current carrying capacity in amperes) of not less than 15 or more than 50. Generally, wires involved are not larger than #6 AWG nor smaller than #14 AWG for copper conductors, and #12 AWG for aluminum or copper clad aluminum conductors. Tap conductors for lighting fixtures (fixture wiring) and other equipment connected to branch circuits may be as small as #18 AWG for copper conductors.

Both wire-to-wire and wire-to-terminal (such as wire-to-terminal parts on receptacles, switches, lighting fixtures or permanent appliances, etc.) connections which are made in the field or in a housing or mobile home factory are included in this study. Connections which are normally made as a part of the manufacturing process of electrical equipment are not included.

This research project was not created in response to reported problems with aluminum wire electrical connections [6] and it is not the intent of this state-of-the-art report to evaluate the use of aluminum wire in branch circuits. However, nearly all recent research concerning branch circuit electrical connections has been addressed to aluminum wiring problems. Pertinent information based on this research is included in this report.

All electrical cables with aluminum conductors in sizes used in residential branch circuits which were listed by Underwriters' Laboratories (U.L.) prior to 1973 have been withdrawn from U.L. listings [7]. U.L. has subsequently listed a number of other electrical cables with specific aluminum alloys [8]. Also, U.L. has revised its requirements for connections listed for use with aluminum conductors [9]. This has out-dated all pre-1973 connectors (such as terminals on receptacles) listed for use with aluminum conductors in residential branch circuits. Information concerning what could or should be done with pre-1973 aluminum wiring installations is outside of the scope of this report and this project.

[1] Figures in brackets refer to references at end of paper.

1.2. Background

In the United States approximately 28,000 electrical contractors employ 237,000 electrical workers and 60,000 overhead workers [10]. (Electrical Contractor Magazine.) They have approximately $12 billion annually in sales. Approximately 35.2 percent of this total is spent on electrical labor, 38.4 percent on materials, and 26.4 percent on indirect expenses, overhead, profit and taxes.

Of the $12 billion in sales, approximately 25.8 percent is for one- and two-family residential, 6.3 percent for apartment residential, 24.6 percent for commercial, 22.3 percent for industrial, 12.0 percent for institutional, and 9.0 percent for other types of occupancies. The $12 billion in sales primarily represents electrical work by contractors in conventional construction and does not include electrical work in mobile homes or factory-built housing. Also, it includes only a small portion of the electrical work done by utilities and only part of the electrical work done by industrial establishments.

The major portion of the electrical work by contractors in conventional residential construction is in branch circuit wiring. The major part of the work of branch circuit wiring is the making of electrical connections, including the installations of outlet, junction or other boxes and the mechanical fastening of electrical cable to boxes. Electrical connections in branch circuit wiring appear to be the primary area in electrical construction where considerable savings in cost and time are almost immediately possible.

a. Fire Hazard Considerations

Electrical wiring and equipment are among the leading causes of accidental fires. In 1971 they accounted for 160,900 of 996,600 building fires. Motors and power-consuming appliances accounted for 62,100 of these fires; wiring and general equipment accounted for the other 98,800 [11]. (NFPA Statistics.) While available statistics are not in sufficient detail to determine how many of these fires involve connections or terminals, it is believed that a large number of them which do not involve motors or other power-consuming equipment are started at connections.

By 1968 field reports indicated that aluminum wiring was sometimes overheating at screw terminals on receptacles in branch circuit residential applications [7]. Further indications of problems with aluminum wiring appeared in 1970 when 25 incidents of fire in 2000 California homes wired with aluminum were believed to have been caused by faulty electrical terminations [6]. Subsequently a study by Underwriters' Laboratories estimated that 80 percent of the failures in branch circuit wiring involved connections and showed that failures involved both aluminum and copper wire installations [9].

b. Electric Shock Considerations

Protection against electric shock and electrocution is a major consideration in determining requirements for electrical installations. Approximately 1,000 deaths annually are attributable to electrocution. Of these approximately 300 are associated with residential occupancies [12] (National Safety Council Statistics).

It is usual practice to require that those parts of electrical equipment operating at 50 volts or more (Sec. 250–3 of NEC) be guarded against accidental contact. It is also usual practice to ground non-current-carrying conductive parts of electrical equipment. Large metal objects, such as metal siding, are often grounded for protection in the event they may come in contact with live electrical conductors. Section 250–44 of the National Code [5] recommends grounding of large metal objects.

c. Industrialized Housing Needs

Nearly all major parts of houses, such as exterior and interior walls, ceiling, and "floor-ceiling" assemblies, incorporate electric wire and equipment (switches, receptacles, lighting fixtures, etc.). Installing the type of electrical systems used in conventional housing becomes an impediment to industrialized or mass-produced housing since it is required that all electrical connections be in junction, outlet, switch or other boxes. The advantages of not requiring that electrical connections be accessible after completion of building construction became apparent with advancements in the construction processes.

1.3. Definitions of Special Terms

Several special terms used throughout this report are defined as follows:

a. Electrical Connection Component

Electrical connection component is defined as all parts of the hardware directly concerned with the proper functioning and safety of the electrical connection. As described below, this would include the continuous current path elements, the dielectric element, and the enclosure element.

b. Continuous Current Path Element

Continuous current path element is defined as the electric connection point or area and electric wire and other parts in the vicinity of the connection point through which current is intended to flow and which are directly involved in the proper functioning and safety of the connection. In conventional construction this would include metal portions of "wire-nuts" in wire-to-wire connections and wire binding screw terminals on wire-to-terminal connections. Also included are the grounding connection point or area; and the wire and metal parts in the vicinity directly involved in the proper functioning and safety of the grounding connection. In this report "continuous current path elements" are generally referred to in the plural because an electric connection usually involves more than one joint or connection.

c. Dielectric Element

Dielectric element is defined as insulating material in the vicinity of the electric connection point or area. Insulating material must completely surround the continuous current path elements. The dielectric element may be "air." This is the case where receptacles or switches are rigidly held in place within an outlet box and electrical connections are made by means of wire binding screws.

d. Enclosure Element

Enclosure element is defined as rigid metallic or non-metallic material which surrounds an electrical connection and prevents persons, other building components or other objects from coming in contact with the continuous current path elements. In conventional construction a switch, outlet or junction box is the enclosure. The same piece of hardware may perform both the function of the dielectric element, which is an electrical function, and the function of the enclosure, which is a mechanical function.

e. Other Building Components

Other building components is defined as parts of the building other than electrical connection components. This would include studs and other structural parts, nails, gypsum board, pipes, ducts, and wiring other than that included in Definition 1.3.b.

2. Traditional Approach

The traditional approach to branch circuit wiring connections is the on-site: (1) fastening of outlet, junction or other boxes to building components, (2) fastening of electrical cable to boxes, and (3) making of electrical connections in boxes. Wire-connectors (wire nuts) are normally used for "wire-to-wire" connections and wire binding screws or studs and nuts having upturned lugs are normally used for "wire-to-terminal" connections. In some cases connections are soldered with a fusible metal alloy. Pressure cable connectors, pressure terminal connectors and soldering lugs are sometimes used.

There have been improvements in electrical cable insulation. New materials have been introduced, such as aluminum wire and non-metallic sheathed cable and non-metallic outlet boxes. However, the traditional approach to branch circuit wiring has changed very little over the past 25 or more years.

3. Current Evaluation System

In the United States, the evaluation and approval of electrical connections and other electrical construction in housing primarily involves three entities, which are; (1) local authorities, (2) the National Electrical Code (NEC) [5] and (3) Underwriters' Laboratories, Inc. (U.L.).

3.1. Local Authorities

Local authorities usually determine legal requirements which apply to electrical construction in their areas. In practice, however, local authorities usually follow the National Electrical Code for installation requirements and approve only manufactured electrical components which have been listed by Underwriters' Laboratories, Inc.

In some cases local authorities adopt the National Electrical Code with modifications. Such modifications usually make legal requirements more restrictive than corresponding NEC requirements. For example, some jurisdictions prohibit the installation of non-metallic sheathed cable [13] or electrical cable with aluminum conductors [7].

The inspection of electrical construction is usually done by local authorities. The National Electrical Code and any local amendments to the NEC are referred to in the event of any controversy concerning wiring methods or requirements. Otherwise, the safety and adequacy of electrical installations are evaluated by the judgment of electrical inspectors.

3.2. National Electrical Code

The National Electrical Code [5] is promulgated under procedures of the National Fire Protection Association (NFPA) and the American National Standards Institute (ANSI). The Rules of Procedure for amending the NEC are detailed in an appendix to the NEC.

The National Electrical Code, as published, is a voluntary standard. However, it affects construction throughout the United States because of its adoption by state, local, or other enforcing authorities. In areas where there are very limited or no legal requirements, or where legal requirements are not rigidly enforced, some contractors still conform to the National Electrical Code. In the event of fire or accident, courts generally accept the National Electrical Code as acceptable good practice. Eight hundred thousand copies of the 1968 NEC, which was superseded in 1971, were published.

The National Electrical Code is an "installation" code. It states in generic terms what may be installed for different types of construction and for given conditions, and sets forth installation requirements. It is a combination of performance (stating what is to be accomplished) and specification (detailing specific methods, materials or components) requirements. An Electrical Code for One and Two Family Dwellings, which is excerpted from the National Electrical Code [14] also has been published.

Responsibility for revision of the NEC is divided among approximately 22 panels (subcommittees) with a correlating committee overseeing and coordinating the work of the panels. The panels consist of representatives from varied interests such as electrical manufacturers, electrical contractors, electrical utilities, electricians, insurance, electrical and building inspectors, and other governmental authorities. The NEC is revised

on a three-year schedule and there are provisions for interim amendments. All properly submitted revisions are considered by the appropriate NEC panel. Approximately 1800 revisions to the 1974 NEC edition have been proposed.

The NEC covers requirements for electrical construction except for the suppliers' or utilities part of electrical systems. Requirements for electrical and communication utilities' facilities are generally covered by the National Electrical Safety Code [15, 16, 17, 18].

It is virtually impossible for new products to enter the market place in any significant quantity unless there is conformity with the National Electrical Code. Because of potential fire and shock hazards of electricity, it is difficult for innovations to gain approval without in-use experience. National Electrical Code requirements are principally the result of long experience with electrical construction.

a. NEC Requirements for Electrical Connections

Section 110–14 Electrical Connections, of the National Electrical Code, which is listed in Item A of the Appendix to this report, requires that connecting devices be "suitable for the purpose." This performance language permits the use of innovative connecting devices which have been properly tested and evaluated by organizations such as Underwriters' Laboratories. Developers of innovative connections do not consider rules strictly relating to electrical connections as being restrictive.

b. NEC Requirements for Boxes

Section 300–15(b) of the National Electrical Code states that a box shall be installed at each conductor splice connection point, outlet, switch point, junction point or pull point for the connection of metal clad cable, mineral insulated metal sheathed cable, aluminum sheathed cable, non-metallic sheathed cable, or other cables, and at each outlet and switch point for concealed knob and tube wiring. (See item B of appendix.) For concealed knob and tube work, splices may be made outside of boxes; however, boxes are required for terminal connections (see item F of appendix). Section 370–6 requires a certain volume of free space in each box depending on the number and size of the conductors and the fittings or devices such as switches or receptacles which are in the box (see item C of appendix). For example, each number 14 conductor requires 2 in^3 of free space; each number 12 requires 2.25 in^3. These requirements concerning boxes appear to constrain innovations.

The requirements concerning boxes appear to constitute an immediate issue which this research project must face. Reference [19] (National Electrical Handbook) states that the "purpose of an outlet box is to provide an enclosure for circuit wire where they are brought out for connection to a fixture or other device. This enclosure is particularly necessary on account of the splices which the box may contain. The enclosure should be made complete by means of a cover of some kind." Boxes are necessary for fire and electrical safety purposes for conventional electrical systems. However, whether boxes are necessary in innovative electrical systems is a very important question. It appears that very significant cost and time saving advancements in branch circuit wiring systems could be effected, almost immediately, if the requirements for boxes were eliminated, provided, of course, that fire and electrical safety aspects were provided for in other ways.

There are exceptions to the requirements for boxes for (1) exposed cable wiring, (2) concealed work in rewiring existing buildings, and (3) wiring in mobile homes. A technical reason for these exceptions is not obvious.

Section 331–11, Devices of Insulating Material, permits the use of switch, outlet, and tap devices of insulating material without the use of boxes in exposed cable wiring and for concealed work for rewiring in existing buildings where the cable is concealed and fished (see item E of appendix).

Section 550–8(j) of the National Electrical Code permits outlet boxes of dimensions less than those required in Tables 370–6(a) (1) and 370–6(a) (2) in mobile homes (see item D of appendix). There is essentially "zero space" for some innovative connections which are described in this paper and are listed by Underwriters' Laboratories (see subsection 10.2 of this report).

Section 550–8(j), however, only applies to mobile homes. A technical reason for less stringent requirements for mobile homes is not known. Actually, mobile homes may need more stringent requirements because they may be subject to more severe vibrations than conventionally built homes.

Requirements for boxes in conventionally-built and factory-built homes need intensive evaluation because of the very significant and very immediate effect they have on housing technology.

c. NEC Accessibility Requirements

There has been a long established requirement that all electrical connections be accessible after building construction has been completed. Section 370–19 of the National Electrical Code states that "junction, pull, and outlet boxes shall be so installed that the wiring contained in them be rendered accessible without removing any part of the building, sidewalk or paving." (See item G of appendix.) In conventional electrical systems there is need for repairing or replacing connections or connecting devices. Because of this it appears certain that inaccessible connections will not be permitted unless there is convincing proof of their durability and safety.

However, with the advent of industrialized housing, there is a growing desire to make use of inaccessible connections. In Operation BREAKTHROUGH, two housing producers proposed using inaccessible "quick make-up" connectors. Neither was used because of the lack of technical knowledge and tests to evaluate the durability of these connectors.

3.3. Underwriters' Laboratories

Nearly all testing for safety of manufactured elec-

trical products is done by Underwriters' Laboratories (U.L.), a non-profit, private corporation. Underwriters' Laboratories lists manufactured products which they have tested and found satisfactory. U.L. develops its own test methods and standards. Non-metallic sheathed cable, armored cable, wire connectors and soldering lugs, and outlet boxes and fittings are some of the electrical products covered by Underwriters' standards which interface with branch circuit electrical connections [20, 21, 22, and 23]. Other U.L. standards which include specifications and tests for wire leads and wire terminals intended for connections to branch circuits, include equipment such as snap switches [24], attachment plugs and receptacles [25], and electric light fixtures [26].

In the case of innovative or other products for which a standard does not exist, the product is evaluated in accordance with the judgment of Underwriters' Laboratories, using established tests or procedures to the extent applicable or possible.

"Testing for Safety" [27], published by Underwriters' Laboratories, describes its purpose, procedures, facilities and equipment, services available, and policy-making councils. Underwriters' Laboratories has no legal authority to "approve" products for installation or sale. U.L. uses the word "list" and not "approve" in referring to products it has found satisfactory. Approval of products is the function of the enforcing authority having jurisdiction. The procedures of most enforcing authorities do not call for listing by Underwriters' Laboratories as the sole criterion for approving electrical products. However, in practice, listing by U.L. usually becomes tantamount to local approval provided local electrical regulations are not more stringent than those of the National Electrical Code, in which case the use of certain types of electrical products may be prohibited [13].

Electrical products are listed in two volumes; Electrical Construction Materials List [28], and Electric Appliance and Utilization Equipment List [29]. Thousands of specific manufactured electrical products are listed in each of these volumes. Additions and deletions to these lists and to other products listed by Underwriters' Laboratories are published quarterly [30].

A long-standing policy of Underwriters' Laboratories is to list only products which may be installed in accordance with the National Electrical Code. Special conditions and instructions governing the use of a product category or a specific listed product are published in their lists [28, 29].

For example, a part of the text for "wire connectors" states "wire connectors are listed for No. 18 AWG or larger copper conductors and/or No. 12 AWG or larger aluminum conductors. They are for use in accordance with the National Electrical Code."

The text, listing a type of receptacle described in subsection 10.2. of this report, states: "Receptacles for factory assembly on type NM or NMC cable in mobile homes without a separate outlet box, 15a, 125v, grounding type Type HW–1."

4. Other Electrical Connection Specifications, Standards and Tests

The state of the art concerning the requirements for and the evaluation of branch circuit electrical connections in the United States is represented by the National Electrical Code and appropriate standards of Underwriters' Laboratories as discussed in subsection 3.2., 3.3. and 6.1. of this report. Other standards, specifications, and test methods which may have some application are listed below.

4.1. American National Standards

The C73 series of American National Standards specifies dimensions and configurations of caps, plugs, and receptacles [31]. The other American National Standard on electrical connections concerns highly reliable soldered connections in Electronic and Electrical Applications [32].

4.2. Federal Specifications

The Index of Federal Specifications [33] lists two electrical connector specifications [34 and 35]. In the context of these Federal Specifications, attachment plugs and receptacles are connectors and the connection between these devices is the primary concern. The permanent connection between a receptacle and the branch circuit wiring is not specifically addressed.

4.3. Military Specifications

There are over 900 military specifications for electrical connectors [36]. Most of these are for very special or very limited applications. References 37 through 41 list some of these specifications. None of these specifications is concerned with electrical connections in branch circuit wiring. A number of test methods to determine various properties or characteristics are described. These tests appear to have little application to this project.

4.4. National Electrical Manufacturers' Association

Standards of the National Electrical Manufacturers' Association concerning electrical connectors generally involve connections using larger wires and applications other than branch circuit wiring. Reference 42 on Electric Power Connectors defines and describes various types of electrical conductors. Test methods are not described.

4.5. American Society for Testing and Materials

Reference 43 describes standard methods for measuring contact resistance of electrical connections (static contacts). (See subsection 8.1. of this report.) Contact resistance is not measured by Underwriters' Laboratories in their test procedures.

5. Field Performance of Electrical Connections

An attempt to determine the field performance of electrical connections is represented by Reference 9. U.L. responded to the aluminum wiring problem [6, 7] by sending 1000 questionnaires to industrial users of electrical equipment and 11,500 questionnaires to electrical contractors and electrical inspectors. The response from industry was 17 percent and from contractors and inspectors was 13.5 percent. The survey is briefly summarized as follows:

(a) There is a usage of copper to aluminum of 4 to 1.

(b) Estimated causes of failure and percent occurrence:

Loose connections	54%
Design	16%
Environment	14%
Improper Metals	9%
Overload Conditions	6%

(c) 71 percent of the failure problems were corrected by replacing damaged parts and 22 percent were corrected by replacing wire.

A second list of more detailed questions was sent by U.L. to 194 electrical inspectors who provided the following information:

(a) Loose connections are caused by failure to tighten screws (workmanship) and/or small bolts, small screwdriver slots and weak connector metals (design).

(b) Wire, particularly aluminum wire, often breaks when being bent to fit into available wiring spaces.

(c) Corrosion due to improper use of dissimilar metals or to wet or damp environments contributed to connector failures.

(d) Consideration of the properties of thermoplastic insulation is necessary to assure that involvement of the insulation in an overheating problem will not be a contributing cause to more rapid deterioration of the connection itself.

6. Electrical Connection Research and Testing

Branch circuit electrical connection research and testing consists principally of U.L. accelerated tests, seven years of testing by the United Kingdom, and unpublished work at the Battelle Memorial Institute. The goals of accelerated testing are (1) to induce, in a much shorter period of time, changes in properties representative of those caused by long-term service, and (2) to relate the time required to induce a property change to that required by long-term service.

The second goal of accelerated testing is seldom fulfilled and the lack of an accurate time relationship between the results of accelerated testing and long-term service makes difficult the interpretation of accelerated test results. Therefore, predictions of durability involve judgmental factors which are based on changes in properties of materials relative to how these materials are installed in systems and the subsequent service conditions of the systems.

6.1. U.L. Accelerated Tests

In the United States acceptance testing of conventional electrical connections in branch circuit wiring is principally the accelerated tests performed by Underwriters' Laboratories [44]. Specific tests include (1) heat cycling with wire disturbance, (2) heat cycling with vibration, (3) environmental and (4) stripping torque.

6.2. Seven-Year Tests in the United Kingdom

British Insulated Callender's Cables Ltd. (BICC) performed tests (high currents, cyclic loading) on connectors not commonly used in the United States or Canada, over a period of seven years [45]. These tests compared the results of using solid copper, copper-clad aluminum and solid aluminum wire.

a. High Current Tests

The effects of high currents on standard connectors and wire were determined by measuring the time to cause failure in typical simulations. Connector temperatures were measured with themocouples and failure was defined as the time taken to reach 175 °C.

Figure 1 shows current (in amperes) plotted against the time to failure (in hours) for a circuit. The dotted portions of the curves are extrapolated. Figure 2 provides data for a lighting circuit.

The significance of these curves is that they show the relative durability of copper, copper-clad aluminum, and solid aluminum wire as a function of wire gage, current rating, and failure. Thirty thousand hours are considered to be equivalent to a 20-year life for wiring.

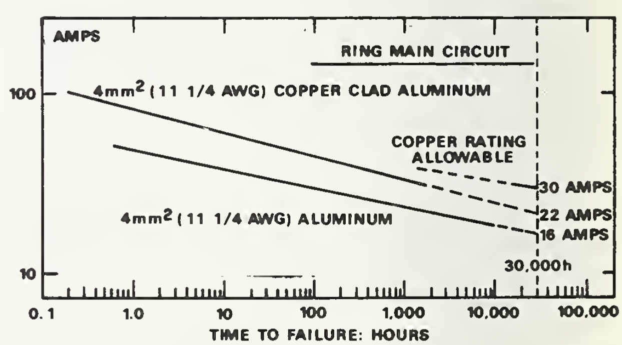

FIGURE 1. *Twenty-year circuit ampacity—ring main circuit (branch circuit).*

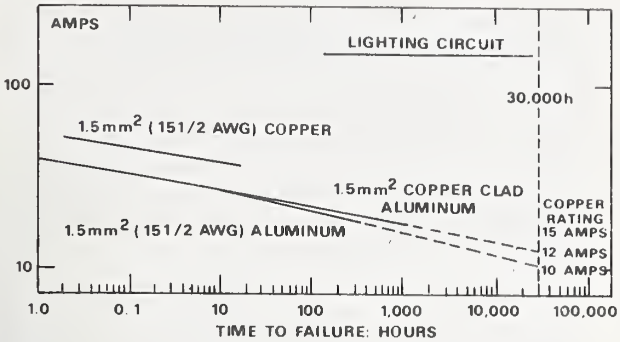

Figure 2. *Twenty-year circuit ampacity—lighting circuit.*

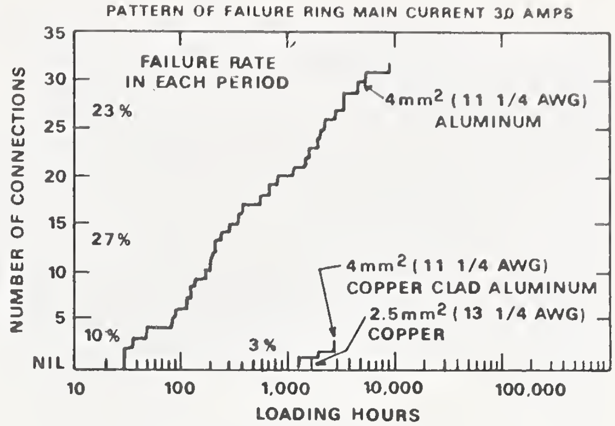

Figure 3. *Service reliability test (the number of aluminum connections failed versus the hours energized—10 percent failed after 100 hours, 27 additional failed after 1000 hours, and 23 percent additional failed after 10,000 hours).*

The number of copper connections failing is 3 percent after 1000 hours.

b. Cyclic Loading Tests

Cyclic loading tests were performed on groups of connectors wired as a ring main circuit with a terminal box between connectors so they could be isolated and replaced. A daily check was made on temperature rise, and a connector was considered to fail when it reached a temperature of 175 °C.

Figure 3 shows the relative durability of connectors wired with copper, copper-clad aluminum and solid aluminum as a function of cyclic loading at 30 amperes. The failure rate of aluminum appears to be clearly unacceptable under these conditions, and the failure rates of copper as well as copper-clad aluminum are questionable.

Figure 4 represents a more practical service condition with cyclic loading at 22 amperes representing typical use of a receptacle in the home. The failure rate of aluminum appears to remain unacceptable under these test conditions while copper-clad aluminum as well as copper exhibited no failures.

The BICC work points out the need for long-term testing of electrical connections with potential conductor materials to establish the validity of acceleration factors. Figure 4 probably represents 6- to 7-year performance for the designs tested. Data is needed for long-term performance of different designs to prove the durability of those designs. Long-term performance testing is especially needed where replacement provisions are not made.

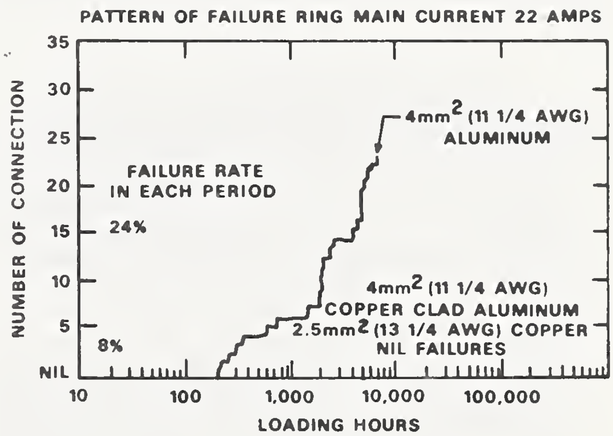

Figure 4. *Service reliability test (the number of aluminum connections failed versus the hours energized—8 percent failed after 100 hours and 24 percent after 10,000 hours).*

Copper and copper-clad connections did not fail after 10,000 hours energized at 22 amperes.

6.3. Battelle Memorial Institute Research (BMI)

Research began in 1970 at the Battelle Memorial Institute in response to field service problems arising from the use of aluminum wiring with conventional connectors. The results of this work have not been published, because it has been funded by private industry sponsors who wish the information to remain proprietary at the present time. This research represents the most significant research effort in the United States on electrical connectors and includes stress relaxation, thermal, and environmental performance testing.

7. Failure Mechanisms

There does not appear to be any published research information which substantiates causes of failures in electric connections. An evaluation of available information (unpublished and published) indicates that failure might occur as a result of one of the three postulated mechanisms listed below.

7.1. Resistance Heating

Fire at electrical connections might be started by resistance heating in the wire-to-connector joints. Resistance heating may be caused by the presence of insulating layers in the joints. The insulating layers may form during power operation by a combination of low contact pressure in the joint and exposure of the joint to elements in the atmosphere which form insulating layers. Overheating accelerates the rate of formation of insulating layers and hence the rate of increase in the resistance of the joint, leading to additional overheating. This is a runaway phenomenon. Overheating might occur to such an extent that combustible material could ignite.

7.2. Loose Connections—Arcing

A loose connection may result in disconnection of a circuit but may also result in overheating. A potential fire hazard is created by arcing in a loose connection. Temperatures sufficiently high to melt metals in the joint may be reached. Accident investigations indicate that molten metal has been ejected explosively from high-voltage motor control centers as electricians opened the door to examine the cause of noises in a panel box.

Two theories can be expressed which might account for such an incident, as follows:

a) Hydrogen

Excessive temperatures in an electrical connection could generate hydrogen chloride by the decomposition of plastic insulation containing chlorine, with subsequent liberation of hydrogen by reaction of hydrogen cholride with metals. Hydrogen might also be produced by the electrolytic decomposition of water. Hydrogen gas might be ignited explosively by an arc in the electrical box.

b) Metal/Oxygen Reaction

Metal might react explosively with a sudden flow of oxygen into an electrical box after arcing has burned all of the oxygen in a box and removed oxide films from the conductor metals. A metal stripped of its oxide film might behave like a pyrophoric material. The tendency for such a reaction to occur increases as the metal changes state from solid to liquid vapor.

7.3. Wire Breakage

In the process of making electrical connections, the wire in the vicinity of the connection may receive stresses which may be a factor in subsequent wire breakage. Subjecting an electrical connection to vibration might increase the wire stresses sufficiently to cause wire breakage or reduce the wire cross section enough to result in overheating. Bending and pulling the wire during installation of connections could result in wire breakage or overheating.

8. Properties and Behavior of Materials Used in Electrical Connections

In conventional systems used in the United States, the current path at the interface in an electrical connection is established mechanically and maintained by a "wire-nut", binding head screw, or other means. Properties discussed in this section assume mechanically established connections. (See 9.2.b. for a discussion of metallurgical bonding.)

8.1. Contact Resistance

Establishing and maintaining a low contact resistance is the principal property necessary for a successful electrical connection. Reference 43 states:

> "Contact resistance is a measure of the functional extent of true metallic contact area that has been achieved in making an electrical connection. High contact resistance indicates poor utilization of the apparent contact interface area with relatively small areas of true metallic contact. Zero contact resistance is achieved with full utilization of the clean contact interface. Acceptably low values of contact resistance are attained with less than complete metallurgical bonding of the contact interface. The practical evaluation and comparison of electrical connections depends in large part on their contact resistance characteristics."

As contact resistance increases, attributes which are directly necessary for the satisfactory performance of electrical connections, particularly "fire safety" (temperature rise), are greatly affected. Much of the other information discussed in this section and in section 9, Materials Property Problems in Electrical Connector Design, concern the problem of maintaining low contact resistance throughout the life of an electrical connection.

8.2. Surface Films

As indicated by Fan [45], surface films which are always present on exposed surfaces of the wire can have much higher resistivities than their base metals, so conduction paths must be created through these surface films or layers when making a connection.

The mechanism which permits current conduction through the oxide layer on copper is designated as "fritting" by Holm [46]. Fritting is defined as a mild electrical breakdown of surface film during current flow. Reference 45 emphasizes that the fritting voltage for a 100 angstrom layer of copper oxide is less than 0.0001 volt, while the fritting voltage for the same thickness of aluminum oxide is 40 volts.

Because of its high fritting voltage, aluminum oxide may interrupt the current path. This potential interruption has resulted in special wire/connector designs, termination techniques, and performance testing for electrical connections terminating aluminum wire.

Virgin metal-to-metal contact should be established and maintained between aluminum wire and other conducting components in the continuous current path of an electrical system if efficient electrical function and safety are to be achieved under required service conditions.

Virgin metal-to-metal contact is reported to be not as important for the fire safety of copper wiring systems because of the low fritting voltage of copper oxide. However, other surface films caused by corrosion might cause overheating in copper wire connections [47].

The significance of an insulating surface layer to the performance of an electrical connection is represented by the curve in Figure 5 [48]. Williamson explains that as long as the resistance of the joint remains small the temperature-dependent processes occur slowly, but when the constriction resistance increases by slow reoxidation at the interface, the temperature rises and this accelerates the reoxidation. The data for Figure 5 were derived by measuring the overall resistance, the current (I), and the temperature of an electrical joint of two aluminum conductors. Williamson then estimates the constriction resistance (R_o) as the difference between the observed resistance and the resistance of an equivalent length of conductor of the same diameter as the joint. Molten aluminum and high temperatures in the electrical joint present the potential for unacceptable fire safety. Williamson concludes: (1) that the interfacial temperature in a well-made joint under normal operating conditions is only a few degrees Celsius above the bulk temperature, and (2) uncertainties about the constriction resistance are due to a lack of knowledge of the way contact spots are distributed over the joint interface.

Figure 5 shows the temperature in a compression joint between two aluminum conductors in an ambient temperature of 20 °C. The abscissa has been plotted in terms of the product of the constriction resistance, measured with a low current at 20 °C and the current through the joint.

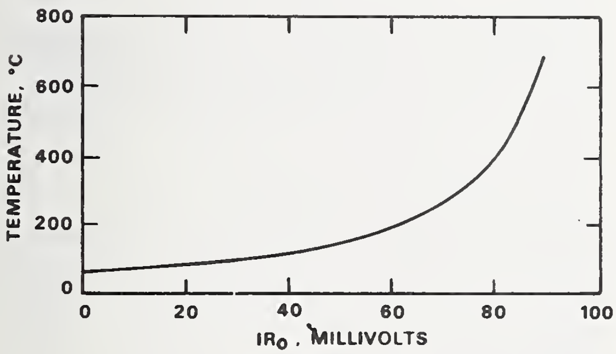

FIGURE 5. *Relation between the temperature created at the interface of a joint and the potential difference across the restriction resistance* [48].

8.3. Effect of Contact Pressure

Reference 45 describes a continuous current path (metal-to-metal contact) through insulating surface layers in wire-to-connector interfaces. Low contact resistance was achieved by the application of high contact pressures as shown in Figure 6. Figure 6 shows that electrical connections wired with copper and copper clad aluminum exhibit low contact resistance at much lower contact pressures than electrical connections wired with aluminum.

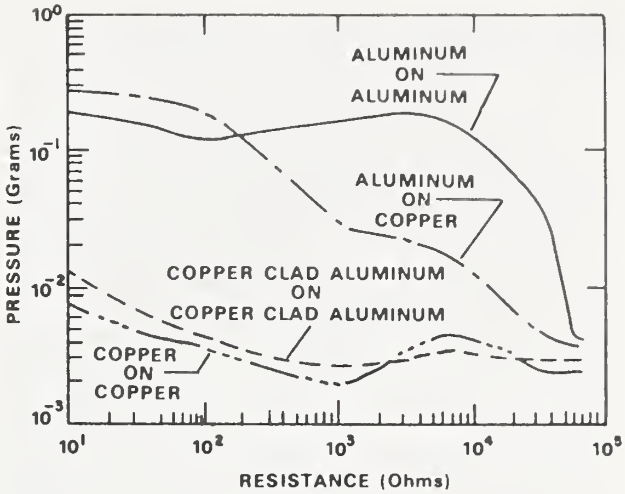

FIGURE 6. *Contact resistance versus contact pressure for electrical connections wired with the indicated conductors.*

8.4. Creep and Stress Relaxation

Once a continuous low resistance current path has been established, it must be maintained under various service conditions.

Creep and stress relaxation present a special problem relative to maintaining a continuous current path over an extended period of time. "Creep" and "stress relaxation" are names for the same property of metals under different conditions. Creep is an increase of strain at a constant stress. Relaxation is a decrease of stress at constant strain. The high contact pressure which is needed to establish metal-to-metal contact applies stress to the wire. Certain metals when under stress in a connector, can flow to reduce the stress. This flow results in a decrease in contact pressure and a possible increase in the oxide surface layer, the contact resistance, and the temperature of the interface. This mechanism is referred to as cold flow, creep, or stress relaxation. Creep occurs at stresses below the yield strength of the metal, and the rate of creep increases with increasing temperature.

Creep of metals such as copper and steel is reported to be not significant at temperatures commonly exhibited by electrical connections.

Some aluminum alloys which were used in electrical systems prior to 1973 exhibit a significant amount of creep or stress relaxation. In conventional electrical connections aluminum wire might exhibt creep to such an extent that the increase in interface temperature is accelerated by the cumulative mechanism of contact pressure decrease, oxide layer increase, and

contact resistance increase. The result is overheating and eventual failure of the connection [45].

8.5. Thermal Expansion and Contraction

Thermal expansion is important in electrical connections when there is a significant difference between the properties of the wire and the connector to an overheating mechanism.

Thermal expansion is also important when wire is improperly installed with a heat-producing gap between the wire and the connector.

The ratio of the coefficients of thermal expansion of the steel connector and the wire is about 2 to 1. If the temperature of the connection increases by some heat-producing mechanism, then differential thermal expansion will lead to increased contact resistance and a further increase in temperature. The wire will tend to expand at a greater rate than the connector while current is flowing, but because of its being confined by the connector it will deform plastically in such a way that on cooling it will have a reduced diameter. During periods of no current flow, the connection cools and the contact pressure at the interface between the wire and the connector decreases as the metals contract. This mechanism may lead to excessive overheating and an accelerated destruction of the connection if the connection is current cycled.

8.6. Diffusion Across Material Boundaries

Diffusion is the spontaneous movement of atoms or molecules within a material or across material boundaries. The importance of diffusion in the long-term performance of electrical connections involving dissimilar metals is the change in properties that may result over an extended period of time. The rate of diffusion increases with the temperature.

Consider a connection with zinc-plated steel connector plates and aluminum wire. Such a connector is common because zinc is applied to steel to impede corrosion of the steel.

If overheating has increased the temperature of the connection, then zinc may diffuse more rapidly into the aluminum wire. The newly-formed alloy of aluminum and zinc would have an increased electrical resistance which might contribute to an accelerated failure through overheating.

8.7. Strength, Ductility, and Hardness

The mechanical properties of copper and aluminum wire are a function of composition and work hardening. Composition and processing variables establish the strength, hardness, and ductility of the wire. Strength and hardness increase and ductility decreases with increasing applied stress. The significance of these properties is that a wire may be so weak that it will fail with a small amount of applied stress or it may be strong and "brittle" so that it will break in bending during installation. The optimum, as-fabricated, properties for aluminum wire as specified by U.L. are a tensile strength of 15,000 to 22,000 psi and a minimum elongation of 10 percent [8].

These properties are also important after termination in a connector because contact pressure can increase the hardness and decrease the ductility of a wire to such an extent that the wire can break on bending after installation.

8.8. Electrical Conductivity

Electrical conductivity measured in percent IACS (International Annealed Copper Standard) is the property of a conductor which indicates the electrical efficiency of the flow of current. Electrical conductivity is the reciprocal of electrical resistivity. The electrical conductivity of aluminum and copper wires decrease as alloys are modified so as to improve properties such as creep, stress relaxation, and ductility, which are related to durability.

9. Materials Properties Considerations in Electrical Connector Design

The purpose of this section is to show how problems with the performance of electrical connections may be minimized by taking materials properties into account in connector design.

9.1. Surface Layers on Wire

One approach to the establishment of a continuous current path through surface layers in wire to connector interfaces requires a special geometry in connector design. This approach involves the use of indium-plated connector plates which contain small indentations on their surfaces which contact the wire. When pressure is applied to the binding head screw of this design the surface layer on the wire is broken as the wire metal is extruded into the indentations making metal-to-metal contact with the connector plates. It is not known what contact pressure is required to achieve metal-to-metal contact by this method, but an ad hoc committee sponsored by U.L. specifies a torque of 12 pound-inches [7].

The purpose of the indium is twofold, first to flow through the breakage of the surface layer and then to inhibit environmental reaction at the connector interface by acting as a barrier to elements in the atmosphere during subsequent operation of the electrical system.

9.2. Creep and Stress Relaxation

There are essentially three approaches to the problem of creep and stress relaxation, which are in the areas of connector design, metallurgical bonding, and materials development.

a. Connector Design Approach

A connector might be designed with spring tension or the equivalent to maintain contact pressure between the connector and the wire.

b. Metallurgical Bonding

The detrimental interfacial surface layer which can form in a mechanical electrical connection could be eliminated by metallurgically bonding the conductor wire to the connectors. Soldering is the only process used in the United States.

Possible improvements in branch circuit electrical connections lies in the fields of welding, cold forming, and explosive bonding. It appears that practical application of these processes could only be done in a factory environment because of equipment requirements.

c. Wire Alloy Development

Nine wiring manufacturers have developed aluminum alloys for electrical wiring which have been accepted by Underwriters' Laboratories as indicated by Reference 8. It should be noted that as of March 29, 1973, this acceptance excludes many of the alloys which are presently installed in homes.

d. Copper Cladding

Aluminum wire can be clad with a metal such as copper to overcome the property changes which result in a thermal failure mechanism. Reference 45 provides the information on copper cladding. Essentially, copper cladding of aluminum wire provides an electrical bond at terminations and prevents the increase in contact resistance initiated by aluminum oxide which triggers creep, overheating, and eventual destruction of an electrical connection. Copper-clad aluminum appears to perform nearly as well as solid copper. A failure mechanism can be postulated for clad aluminum if the coating is perforated and exposed to moisture. Under these conditions the wire would tend to corrode at an accelerated rate and promote overheating and wire breakage.

e. Nickel Plating

The same performance comments that apply to copper-clad aluminum also apply to nickel-plated aluminum. The advantage of nickel-plated aluminum wire is its reported lower cost compared to copper, copper-clad, and the new U.L. listed aluminum alloys.

10. Recent Innovations

The principal developments of innovative electrical connections for branch circuit wiring in housing are described below. Information concerning innovative electrical connections is based on information published by the organizations developing the products described, in engineering or test reports concerning these products, on examination of the products and on discussions with people concerned with their development.

10.1. Electrical Harness

For the Operation BREAKTHROUGH program, an electrical harness for use in branch circuit wiring was developed. The basic idea was the adaptation of the principles of automobile electrical harnesses (12-volt systems) to electrical systems in housing (nominal 115- and 230-volt systems).

Each harness consisted of a central junction box or circuit breaker panel and a network of legs of predetermined length using outlets and switches specifically designed for attachment in controlled, high-volume, factory assembly lines. The junction boxes were located at ceiling fixtures or other convenient access points such as closets, utility or service areas. A housing module electric power distribution system consisted of one or more spider harnesses installed at the housing producer's plant.

The system used conventional materials and components. Conventional non-metallic sheathed cable was used. The switches and outlets were of conventional design insofar as switching actions and face configurations of receptacles are concerned. The unique characteristics of the switches and outlets were the wire was factory terminated and an integral junction box was used. The switch and outlet designs included a back case cover, made of electrical insulation material, which functioned as an integral part of the junction box. The principal waivers of the National Electrical Code provisions which were necessary to permit the use of this harness were those requiring a specific volume of "free space" within the box. (See sec. 3.2.b. of this report.)

In this system all electrical connections were made in the factory producing the electrical harness. In the housing producers' factory, only mechanical connections were necessary. Portions of U.L. Standards 20 (Snap Switches), 498 (Attachment Plugs and Receptacles) and 514 (Outlet Boxes and Fittings) were used as a guide in the acceptance testing of the harness system [24, 25, 23]. The test results, which included sixteen different types of tests, appeared to be satisfactory when compared to criteria established by Underwriters' Laboratories for similar conventional components. The tests were actually of the harness and not specifically of the electrical connections.

The economic justification for this innovative electrical harness was the saving of labor in a housing producer's factory. Estimates were made that the costs of materials, if there were volume production, would be about one-third more than materials in a conventional electrical system. However, it was estimated that installation labor would be cut, possibly by as much as 70 or 80 percent.

The question of replaceability in the event of failure of one of the components such as a switch or receptacle was considered. It was determined that components could be replaced with reasonable effort with corresponding conventional devices as long as sufficient slack was left in the cable. A minimum of 12 inches for each device or for each leg was recommended.

10.2. Split-beam Receptacles

The most successful innovation concerning electrical connections in branch circuit wiring up to the present time has been split-beam receptacles. Non-metallic sheathed cable is prepared by a special tool which cuts the insulation but not the wire, and positions the wire in the proper position for quick placement into one

piece of a two-piece receptacle. The special tool (costing about $50.00) is then used to clamp the receptacle together making a non-visible electrical connection within the receptacle.

These receptacles have, within the last year, received widespread use in mobile homes and limited use in factory-built and conventionally built homes. National Electrical Code provisions concerning the box (see 3.2.b.) have been the principal reasons for their non-use in housing. Special NEC exceptions for mobile homes and for re-wiring in existing buildings have been taken advantage of for its use in limited applications. (See appendix.)

These receptacles, which do not employ a separate "box," cost more than conventional receptacle assemblies. The economic justification for this device, however, is the saving on installation labor, either in a housing factory or in conventionally-built housing.

Underwriters' Laboratories has issued a fact-finding report on this device. Underwriters' subjected this device to the tests which they believed relevant. Tests used for conventional devices, such as U.L. 498 on Attachment Plugs and Receptacles [25] were, in general, used as a guide. U.L. also subjected these devices to the vibration test outlined in [27] to simulate the vibrations encountered from movement of land transportation vehicles. Tests to simulate time were not made. As a result of the tests, U.L. has listed these devices for applications permitted by the National Electrical Code [5].

The question of replaceability was examined by Underwriters' and it was determined that these devices could be replaced by a conventional receptacle with reasonable effort as long as there was sufficient slack left in the cable during installation. It would be difficult to get less than 18 in of slack if the installation were done in accordance with recommended procedures because of the amount of cable needed to operate the special tool.

Development work is being done on a replacement receptacle which would not require a special tool for its installation. Development of split-beam switches, lighting fixtures, and appliance mountings on the same general principles used in the innovative receptacle is underway. Completion of this work with a satisfactory evaluation by proper authorities would permit the use of this system of electrical connections for nearly all normal applications in branch circuit wiring.

10.3. Quick Splicing Connectors

Quick splicing connectors were developed by at least two manufacturers in response to Operation BREAKTHROUGH opportunities.

The intent was to use these connectors without boxes. Otherwise it was contended that the innovations would not be feasible or competitive. However, for lack of technical knowledge these connectors were permitted to be installed only in accessible enclosures which contained no combustible materials. Because of this and construction schedules, the Operation BREAKTHROUGH housing producers did not use these connectors and installed conventional wiring systems.

10.4. Baseboard Receptacle System

An innovative wiring system was developed on an Operation BREAKTHROUGH Type B contract [49]. This development was concerned primarily with an economical way of providing more electrical receptacles in each room of a building. The principal features of this development concerned the connection of attachment plugs to receptacles and not permanent connections in branch circuit wiring. However, this system would eliminate some connections which would ordinarily be made in branch circuits. Only prototypes of this system have been developed.

11. Research Considerations of Innovative Electrical Connections

Tests have been run (see subsection 10.2. of this report) on innovative concepts which appear to meet or exceed the acceptance requirements of Underwriters' Laboratories.

The principal reason preventing the application of these innovative systems in the field is the potential use of wiring materials other than copper and the lack of durability data.

The technical factors of greatest importance to the durability performance of innovative electrical connections are temperature-increasing mechanisms and materials properties which will result in failures of the continuous current path.

Adequate metal-to-metal contact should be established during installation and maintained during service to minimize temperature increases.

Materials for a mechanical-type electrical connection should be selected with the required strength and ductility to prevent breakage during installation and service.

These materials should also exhibit properties which will not increase the temperature of the electrical connection above an acceptable operating level.

Metal-to-metal contact can be measured directly by destructive examination. However, destructive examination can be useful when related to non-destructive indirect performance measurements.

Contact resistance can be measured electrically and can be related to joint temperatures. More information is needed concerning contact resistance, contact temperture, contact pressure, and metal-to-metal contact with time. A method is needed to measure the contact temperature at the interface between the wire and the connector.

The development of the above measurement techniques would permit the indirect determination of metal-to-metal contact and contact temperatures during the performance testing of electrical connections under cyclic load.

Measurement techniques should be first developed and then applied to the performance testing of innovative electrical connections. The following performance testing is needed:

1. Accelerated tests should be performed to provide data which can be related to the performance of electrical connections under real life conditions. The

basis for acceleration factors, such as cycles, cycle times, current overload, ambient temperature, and aggressive environment, is not presently known.

2. Long-term (10,000 hours) cyclic loading tests at currents typical of household use should be performed to establish data for the performance of electrical connections under real life conditions.

3. Accelerated environmental tests should be performed in aggressive laboratory environments to provide data which can be related to the performance of electrical connections exposed to environments in the field (various geographic locations) such as marine, industrial, et al. The relationship between accelerated environmental results and field environmental results is not known.

4. Long-term (10,000 hours) exposure of electrical connections to field environments should be performed to provide data which can be related to accelerated environmental test data.

This research is needed to establish the validity of acceleration factors and to enable the prediction of the long-term thermal performance of innovative electrical connections based on the results of accelerated performance tests.

Additional research is needed to develop performance tests which will ensure the structural integrity of electrical connections relative to strength and ductility requirements.

12. Summary

1. In the United States the principal basis for the evaluation and approval of electrical connections in branch circuit wiring is the judgment of local electrical inspectors; these are men with practical experience in conventional electrical construction.

2. The National Electrical Code [5] is the principal guide covering the installation of electrical wire and equipment, including the requirements for and the methods of making field electrical connections; unless an innovation can be installed in accordance with the NEC, it will be unable to attain widespread use in the market place.

3. Underwriters' Laboratories requirements and tests are the principal criteria applying to the components interfacing with branch circuit electrical connections.

4. As a result of the use of aluminum wire, research and proposed performance-test programs concerning the failure and hazard mechanisms of branch circuit electrical connections, including some durability aspects, are now under way at Underwriters' Laboratories and Battelle Memorial Institute (see subsections 6.1. and 6.3. of this report).

5. In the construction of both conventional and factory-built housing the traditional system of installing electrical boxes at switch, outlet and junction points, the mechanical fastening of electrical cable to boxes and the making of electrical connections in boxes, are required by the National Electrical Code and most local jurisdictions. It is the requirements for "boxes" and not specifically the requirements for electrical connections which appear to constrain innovation in branch circuit wiring systems (see subsection 3.2.b.).

6. There are some exceptions in the National Electrical Code to the requirements for "boxes." These exceptions apply to mobile homes, to exposed cable wiring and to concealed work in rewiring existing buildings.

7. Electrical connections have failed under field service conditions and some of the overheating-type failures are believed to have been the cause of fires. Wire breakage failures have occurred as a result of wire being bent during installation.

8. Some failures are believed to have been caused by abnormal temperature increases of wire-connector interfaces. The temperature increases are caused by a variety of short and long-term mechanisms which increase the contact resistance at the wire-connector interfaces.

9. Performance tests are needed which measure the properties of electrical connections as they relate to durability and overheating aspects.

10. Measurement techniques are needed to establish a quantitative relationship between contact resistance, contact temperature, contact pressure, and metal-to-metal contact with time under cyclic loading conditions.

11. Data are needed to establish the validity of acceleration factors and to enable the prediction of the long-term thermal performance of innovative electrical connections based on the results of accelerated performance tests (see section 6 and 11 of this report).

12. Metallurgical bonding represents an innovative approach which may avoid the thermal failure potential problem inherent in mechanical-type electrical connectors.

13. Considerable uncertainty is associated with an evaluation of the durability of electrical connectors, because very few applicable data are available and much of the available information is proprietary.

13. Recommendations

1. Initiate a research program to develop information and tests on the performance of innovative electrical connectors. This program would consist of the following parts:

(a) Establish an interface with organizations conducting on-going electrical connector testing to obtain information and perform routine testing.

(b) Develop techniques for measuring the properties of electrical connectors with time under cyclic loading conditions.

(c) Study the validity of acceleration factors to enable the prediction of the long-term thermal performance based on short- and long-term data.

2. Obtain information on metallurgical bonding to permit an evaluation of this innovative approach.

3. Develop interim performance criteria and tests.

4. Make a study of the technical criteria and parameters concerning the necessity of "box" requirements for branch circuit wiring.

5. Make a study concerning the parameters, the performance criteria and the feasibility of non-accessible electrical connections in housing.

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Appendix. NEC Requirements Which Directly Affect Innovative Electrical Connections

A. NEC Requirements for Electrical Connections (see subsection 3.2.a.)

Article 110 General 70-15

110-14. Electrical Connections. Because of different characteristics of copper and aluminum, devices such as pressure terminal or pressure splicing con-

nectors and soldering lugs shall be suitable for the material of the conductor and shall be properly installed and used. Conductors of dissimilar metals shall not be intermixed in a terminal or splicing connector where physical contact occurs between dissimilar conductors (such as copper and aluminum, copper and copper-clad aluminum, or aluminum and copper-clad aluminum), unless the device is suitable for the purpose and conditions of use. Materials such as solder, fluxes, inhibitors, and compounds, where employed, shall be suitable for the use and shall be of a type which will not adversely affect the conductors, installation, or equipment.

(a) Terminals. Connection of conductors to terminal parts shall insure a thoroughly good connection without damaging the conductors and shall be made by means of pressure connectors (including set-screw type), solder lugs or splices to flexible leads except that No. 8 or smaller solid conductors and No. 10 or smaller stranded conductors may be connected by means of wire-binding screws or studs and nuts having upturned lugs, or the equivalent. Terminals for more than one conductor and terminals used to connect aluminum shall be of a type suitable for the purpose.

(b) Splices. Conductors shall be spliced or joined with splicing devices suitable for the use or by brazing, welding, or soldering with a fusible metal or alloy. Soldered splices shall first be so spliced or joined as to be mechanically and electrically secure without solder and then soldered. All splices and joints and the free ends of conductors shall be covered with an insulation equivalent to that of the conductors or with an insulating device suitable for the purpose.

B. NEC Requirements for Boxes (see subsection 3.2.b.) Note particularly 300–15(b) below.

Article 300 Wiring Methods—General 70–93

300–15. Boxes or Fittings Where Required.

(a) Box or Fitting. A box or fitting shall be installed at each conductor splice connection point, outlet, switch point, junction point or pull point for the connection of conduit, electrical metallic tubing, surface raceways or other raceways.

Exception No. 1: A box or fitting is not required for a conductor splice connection in surface raceways, wireways, header ducts, multi-outlet assemblies and auxiliary gutters having a removable cover which is accessible after installation.

Exception No. 2: As permitted in Section 410–26.

(b) Box Only. A box shall be installed at each conductor splice connection point, outlet, switch point, junction point, or pull point for the connection of metal-clad cable, mineral-insulated metal-sheathed cable, aluminum-sheathed cable, nonmetallic-sheathed cable, or other cables and at each outlet and switch point for concealed knob-and-tube wiring.

Exception No. 1: As permitted by Section 336–11 for insulated outlet devices supplied by nonmetallic-sheathed cable.

Exception No. 2: As permitted by Section 410–60 for rosettes.

Exception No. 3: Where accessible fittings approved for the purpose are used for straight-through splices in mineral-insulated metal-sheathed cable.

C. NEC Requirements Concerning Free Space in Boxes (see subsection 3.2.b.)

Article 370 Boxes and Fittings 70–165

370–6. Number of Conductors in a Box. Boxes shall be of sufficient size to provide free space for all conductors enclosed in the box.

The provisions of this Section shall not apply to terminal housings supplied with motors. See Section 430–12.

Sections 370–6(a) and (b) do not apply to conductors used for rewiring existing raceways as referred to in Table 1, Chapter 9.

(a) The maximum number of conductors, not counting fixture wires, permitted in outlet and junction boxes shall be as in Tables 370–6(a)(1) and (a)(2) with the exceptions noted.

Tables 370–6(a)(1) and (a)(2) apply where no fittings or devices such as fixture studs, cable clamps, hickeys, switches or receptacles, are contained in the box and where no grounding conductors are part of the wiring within the box. Where one or more fixture studs, cable clamps or hickeys are contained in the box, the number of conductors shall be one less than shown in the Tables; an additional deduction of one conductor shall be made for each strap containing one or more devices; and a further deduction of one conductor shall be made for one or more grounding conductors entering the box. A conductor running through the box is counted as one conductor, and each conductor originating outside of the box and terminating inside the box is counted as one conductor. Conductors, no part of which leaves the box, are not to be counted. The volume of a wiring enclosure (box) shall be the total of the volume of the assembled sections.

(b) For combinations or conductor sizes not shown in Tables 370–6(a)(1) and (a)(2), Table 370–6(b) shall apply.

(c) Boxes, other than those described in Tables 370–6(a)(1) and 370–6(a)(2), shall be durably and legibly marked by the manufacturer with their cubic-inch content. All boxes shall be durably and legibly marked with the manufacturer's name or trademark.

TABLE 370–6(a)(1). *Deep Boxes*

Box Dimensions, Iinches Trade Size	Cubic Inch Cap.	Maximum No. of Conductors No. 14	No. 12	No. 10	No. 8
3¼ x 1½ Octagonal	10.9	5	4	4	3
3½ x 1½ Octagonal	11.9	5	5	5	3
4 x 1½ Octagonal	17.1	8	7	6	5
4 x 2⅛ Octagonal	23.6	11	10	9	7
4 x 1½ Square	22.6	11	10	9	7
4 x 2⅛ Square	31.9	15	14	12	10
4 11/16 x 1½ Square	32.2	16	14	12	10
4 11/16 x 2⅛ Square	46.4	23	20	18	15
3 x 2 x 1½ Device	7.9	3	3	3	2
3 x 2 x 2 Device	10.7	5	4	4	3
3 x 2 x 2¼ Device	11.3	5	5	4	3
3 x 2 x 2½ Device	13	6	5	5	4
3 x 2 x 2¾ Device	14.6	7	6	5	4
3 x 2 x 3½ Device	18.3	9	8	7	6
4 x 2⅛ x 1½ Device	11.1	5	4	4	3
4 x 2⅛ x 1⅞ Device	13.9	6	6	5	4
4 x 2⅛ x 2⅛ Device	15.6	7	6	6	5

See Section 370–18 where boxes are used as pull and junction boxes

TABLE 370–6(a)(2). *Shallow Boxes*

Box Dimensions, In Trade Size	Maximum Number of Conductors No. 14	No. 12	No. 10
3¼	4	4	3
4	6	6	4
1¼ x 4 Square	9	7	6
4 11/16	8	6	6

Any box less than 1½-in deep is considered to be a shallow box.

TABLE 370–6(b). *Volume Required Per Conductor*

Size of Conductor	Free Space Within Box for Each Conductor
No. 14	2. in³
No. 12	2.25 in³
No. 10	2.5 in³
No. 8	3. in³
No. 6	5. in³

D. Exceptions to Box Requirements in Mobile Homes (see 550–8(j) below).

Article 550 Mobile Homes and Parks 70–369

550–8. Wiring Methods and Materials. Except as specifically limited in this Section the wiring methods and materials included in this Code shall be used in mobile homes.

(a) Nonmetallic outlet boxes are acceptable only with nonmetallic cable.

(b) Nonmetallic cable located 15 in or less above the floor, if exposed, shall be protected from physical damage by covering boards, guard strips, or conduit. Cable likely to be damaged by stowage shall be so protected in all cases.

(c) Metal-clad and nonmetallic cables may be passed through the centers of the wide side of 2-in by 4-in studs. However, they shall be protected where they pass through 2-in by 2-in studs or at other studs or frames where the cable or armor would be less than 1½ in from the inside or outside surface. Steel plates on each side of the cable, or a tube, with not less than No. 16 MSG wall thickness, are required to protect the cable. These plates or tubes shall be securely held in place.

(d) Where metallic faceplates are used they shall be effectively grounded.

(e) If the range, clothes dryer, or similar appliance is connected by metal-clad cable or flexible conduit, a length of free cable or conduit should be provided to permit moving the appliance. The cable or flexible conduit should be adequately secured to the wall. Clearance space behind a range may provide the required protection when a range is connected by Type SE cable. When used, Type SE cable shall have an identified and insulated neutral plus an equipment grounding conductor. Nonmetallic-sheathed cable (Type NM) shall not be used to connect a range or dryer.

This does not prohibit the use of Type NM cable between the branch-circuit overcurrent protective device and a range or dryer receptacle.

(f) Rigid metal conduit shall be provided with a locknut inside and outside the box, and a conduit bushing shall be used on the inside. Inside ends of the conduit shall be reamed.

(g) Switches shall be rated as follows:

(1) For lighting circuits, switches shall have a 10-ampere 125-volt rating; or higher, if needed for the connected load.

(2) For motors or other loads, switches shall have ampere or horsepower ratings or both adequate for loads controlled. (An "AC general-use" snap switch may control a motor 2 horsepower or less with full-load current not over 80 percent of the switch ampere rating.)

(h) At least 4 in of free conductor shall be left at each outlet box except where conductors are intended to loop without joints.

(i) Under-Chassis Wiring. (Exposed to Weather).

(1) When outdoor or under-chassis line-voltage wiring is exposed to moisture or physical damage, it shall be protected by rigid metal conduit. The conductors shall be suitable for wet locations.

Exception: Electrical metallic tubing may be used when closely routed against frames and equipment enclosures.

(2) The cables or conductors shall be Type NMC, TW, or equivalent.

(j) Outlet boxes of dimensions less than those required in Tables 370–6(a)(1) and 370–6(a)(2) may be used provided the box has been tested and approved for the purpose.

(k) Boxes, fittings and cabinets shall be securely fastened in place.

Exception: Snap-in type boxes or boxes provided with special wall or ceiling brackets that securely fasten boxes in walls or ceilings may be used.

E. Exceptions to Box Requirements in Exposed Cable Wiring and for Concealed Work for Rewiring in Existing Buildings

Article 336 Nonmetallic-Sheathed Cable 70–135

336–11. Devices of Insulating Material. Switch, outlet, and tap devices of insulating material may be used without boxes in exposed cable wiring, and for concealed work for rewiring in existing buildings where the cable is concealed and fished. Openings in such devices shall form a close fit around the outer covering of the cable and the device shall fully enclose that part of the cable from which any part of the covering has been removed.

Where connections to conductors are by binding-screw terminals, there shall be available as many terminals as conductors, unless cables are clamped within the structure and terminals are of a type approved for multiple conductors.

F. Splices—Concealed Knob-and-Tube Work

Article 324 Concealed Knob-and-Tube Work 70–127

324–11. Splices. Splices shall be made only where close to knobs or tubes using solder or specially approved splicing devices. In line or strain splices shall not be used.

G. NEC Requirements for Accessible Electrical Connections (see subsection 3.2.3).

Article 370 Boxes and Fittings 70–169

370–19. Junction, Pull and Outlet Boxes to Be Accessible. Junction, pull and outlet boxes shall be so installed that the wiring contained in them may be rendered accessible without removing any part of the building, sidewalks or paving.

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In the Operation BREAKTHROUGH research and demonstration program the U.S. Department of Housing and Urban Development became concerned with the inability to properly evaluate innovative electrical connections. Long life requirements, fire safety considerations, the lack of adequate technical information, and long established conventional practices and evaluation procedures have led to slow-changing regulations concerning electrical connections used in branch circuit wiring in housing. This report discusses the present methods of evaluating electrical connections, the technical parameters involved, and innovative electrical connection developments. Innovations involving electrical connections may lead to significant advancements in housing construction if it could be demonstrated that functional and safety requirements over the expected life of the electrical connections were adequately satisfied. Research is needed to enable prediction of long term performance of electrical connections based on the results of accelerated performance tests.

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